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Dielectric spectroscopy in agriculture

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Abstract

Reported measurements of the dielectric properties or permittivities over broad frequency ranges for some agricultural materials are cited, and graphical data from the cited literature are presented. They include 50-kHz to 12-GHz frequency-domain permittivity data for adult rice weevils and hard red winter wheat, time-domain reflectometry data for the same insects from 30 MHz to 1 GHz, frequency-domain data from 200 MHz to 20 GHz for adults of the lesser grain borer, 200-MHz to 20-GHz data for apple juice and fresh peaches, and 10-MHz to 1.8-GHz data, as a function of temperature, for whey protein gel and navel orange tissue. Interpretation of the data showed that selective dielectric heating of rice weevils in wheat could be expected between 10 and 100 MHz but not at microwave frequencies. For fresh fruit and vegetable tissues, temperature dependence of the dielectric constant was minimal at some frequency in the 20–120 MHz range with a positive temperature coefficient below that frequency and a negative temperature coefficient at higher frequencies. Between 10 and 300 MHz, the loss factor can be very well expressed as a linear function of the log of frequency and temperature. With further study dielectric spectroscopy may be useful in detecting product quality factors.
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1. Introduction

Dielectric properties or permittivity of agricultural products are of interest for several reasons. They include the sensing of moisture content in these products through its correlation with the dielectric properties of cereal grain and oilseed crops, the influence of permittivity on the dielectric heating of product at microwave or lower radio frequencies, and the potential use of permittivities for sensing quality factors other than moisture content.

Information on dielectric properties across broad ranges of frequency, which implies dielectric spectroscopy for efficient determination, has been of interest in assessing the best frequency range to use for selective dielectric heating of insects that infest grain and other products, and more recently the frequency and temperature dependence of the permittivities of a few agricultural materials have been investigated. It is the purpose of this article to review briefly some of these previous studies and present some of the resulting information for those interested in dielectric spectroscopy applications.

Throughout this paper, the term 'permittivity' implies the complex permittivity relative to free space, $\varepsilon = \varepsilon' - j\varepsilon''$, where the real part, ε', is called the dielectric constant, and the imaginary part, ε'', is called the dielectric loss factor and includes all losses, mainly those due to dipolar relaxation and ionic conduction.

2. Insect control studies

Early measurements of the permittivity of adult rice weevils, *Sitophilus oryzae* L., and hard red winter wheat, *Triticum aestivum* L., were obtained at frequencies from 250 Hz to 12 GHz with an assortment of eight different

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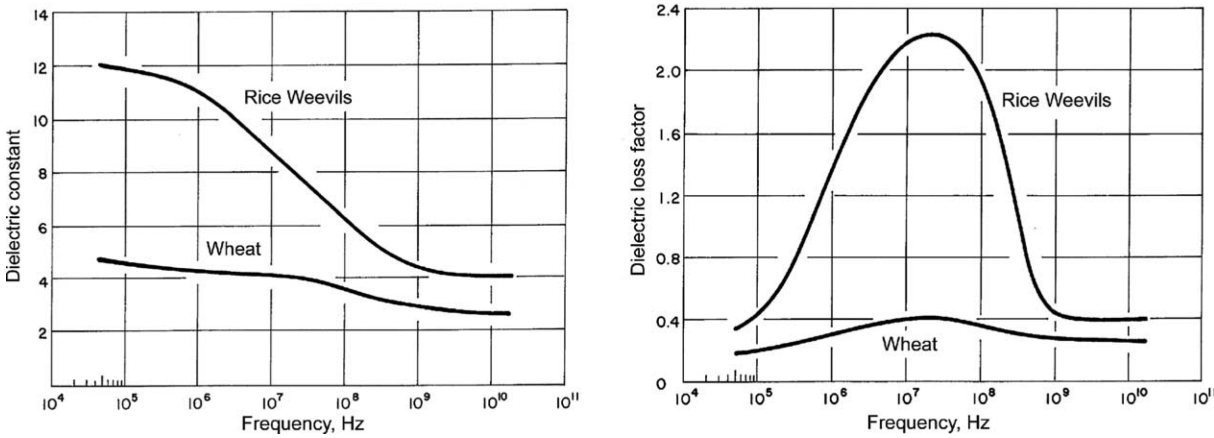

Fig. 1. Dielectric properties of bulk samples of adult rice weevils from 50 kHz to 12 GHz at 24 °C and 0.49 g/ml bulk density [1].

frequency-domain measurement systems, each covering a narrow range of frequencies [1]. Resulting permittivity measurements for the range from 50 kHz to 12 GHz, which covers a broad range of dispersion that includes useful frequencies for dielectric heating, are shown in Fig. 1. The frequency range from about 10 to 100 MHz was identified as the optimum range for selectively heating the insects, where the loss factor of the insects was about five times greater than that of the wheat. This expectation was confirmed by separate exposures to dielectric heating of wheat infested with rice weevils at 39 MHz and 2.45 GHz [2]. Complete insect mortality was achieved at the lower frequency with a wheat temperature of 40 °C, whereas wheat temperatures above 80 °C were required for comparable mortality at 2.45 GHz.

Time-domain reflectometry (TDR) techniques were also used to measure the dielectric properties of rice weevils, wheat, and alfalfa seed [3]. Results for rice weevils, shown in Fig. 2, which were obtained by multiple-reflection TDR measurements, agreed reasonably well with the earlier data of Fig. 1 with respect to frequency dependence of the bulk samples of insects, showing a relaxation frequency at about 40 MHz.

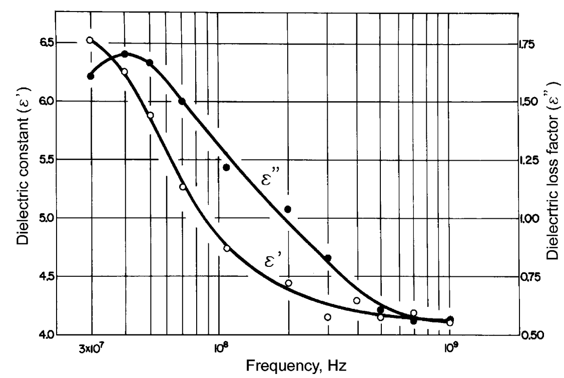

Fig. 2. Frequency dependence of the dielectric properties of adult rice weevils (bulk sample) at 0.49-g/cm^3 bulk density and 25 °C, as determined by multiple-reflection TDR measurements [3].

Permittivities of four species of stored-grain insects were more recently measured with an open-ended coaxial-line probe from 200 MHz to 20 GHz as a function of temperature [4]. Data for one species, the lesser grain borer, *Rhyzopertha dominica* (F.), are shown in Fig. 3. Both the dielectric constant and loss factor generally decreased with increasing frequency and indicated

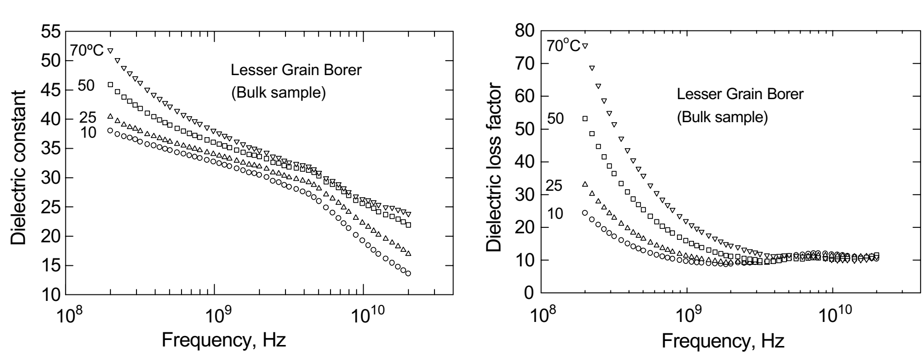

Fig. 3. Dielectric properties of a homogenized sample of adults of the lesser grain borer measured with open-ended coaxial-line probe and network analyzer at indicated temperatures and a density of 1.024 g/cm^3 [4].

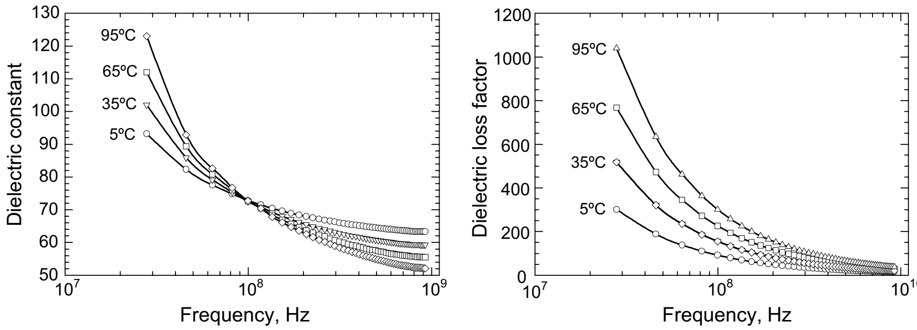

Fig. 4. Frequency dependence of the permittivity of a whey protein gel of 74% moisture content, w.b., and density of 1.05 g/cm^3 at indicated temperatures [5,6].

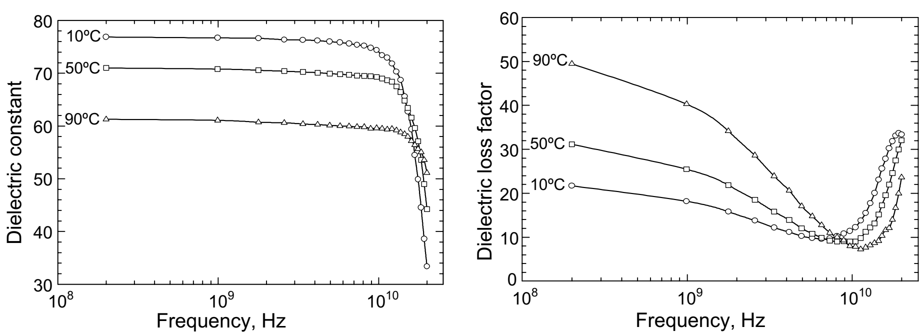

Fig. 5. Frequency dependence of the dielectric properties of apple juice at indicated temperatures (88.5% water) [5,6].

no likelihood that the insects could be better controlled by dielectric heating at higher frequencies.

3. Food materials

The open-ended coaxial-line technique was also used to determine the dielectric behavior of a few food materials with respect to frequency and temperature dependence [5,6]. Results for a whey protein gel are shown in Fig. 4. A reversal of the temperature coefficient for the dielectric constant is observed at about 100 MHz, above which it seems reasonable to conclude that dipolar mechanisms are dominant and below which ionic conduction is the dominant mechanism.

Measurements on apple juice of 88.5% water content are shown in Fig. 5 where the influence of liquid water dielectric relaxation is evident and ionic conduction is the likely explanation for losses at the lower frequencies.

4. Fruits and vegetables

Open-ended coaxial-line probe permittivity measurements were taken with a network analyzer to study the frequency dependence of the dielectric constant and loss factor of many fresh fruits and vegetables in the range from 200 MHz to 20 GHz [7]. The possibility of sensing maturity of fresh peaches, *Prunus persica* (L.), was also explored [8]. In Fig. 6, some differences in the dielectric constant at lower frequencies and differences in the loss factor at higher frequencies can be noted, indicating some potential for developing a permittivity-based maturity index, but much further work would be needed for proper assessment of the technique.

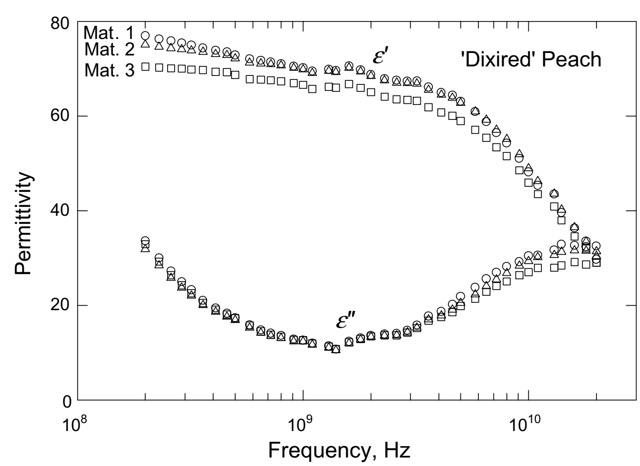

Fig. 6. Frequency dependence of the dielectric properties at 23 °C of 'Dixired' peaches at first, second and third stages of tree-ripe maturity [8].

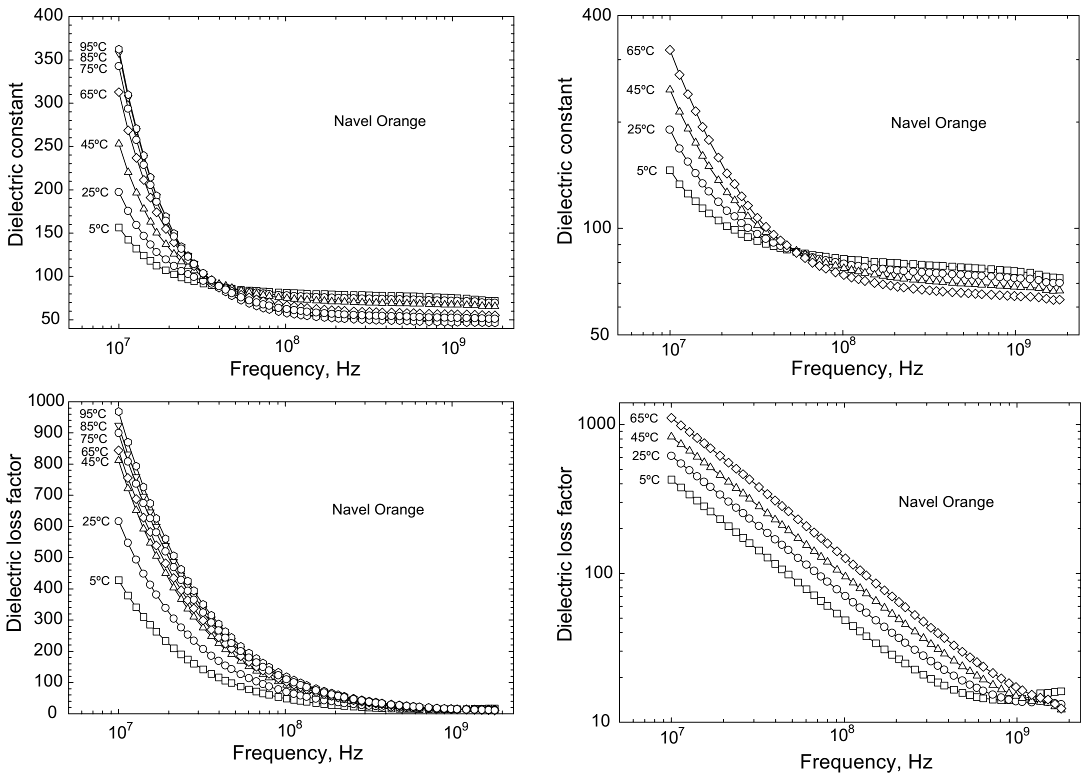

Fig. 7. Frequency and temperature dependence of fresh navel orange dielectric properties from 10 MHz to 1.8 GHz (linear and logarithmic plots for the dielectric constant and loss factor) [10].

Open-ended coaxial-line probe measurements were recently taken on tissue of nine different fresh fruits and vegetables over the frequency range from 10 MHz to 1.8 GHz as a function of temperature [9]. Resulting data for navel orange, *Citrus aurantium* subsp. Bergamia, tissue are shown in Fig. 7. The frequency for zero temperature dependence, at which the temperature coefficient reverses its sign, was about 50 MHz. Using a log–log plot to better separate the higher frequency data revealed a linear dependence between loss factor and both frequency and temperature as shown in Fig. 7 for the frequency range from 10 to 300 MHz [10]. This was true for all nine fruits and vegetables tested. The consequent three dimensional plot for the navel orange tissue is shown in Fig. 8.

Inspection of the permittivity curves in Fig. 7 shows that the reversal of the sign of the temperature coefficient evident for the dielectric constant is not evident for the dielectric loss factor. However, there are most likely multiple effects superimposed, and dielectric relaxations associated with forms of bound water [11] and biological cell consitutents are masked by the large ionic conduction at the lower frequencies. The reversal of the temperature coefficient for the loss factor at the high end of the frequency range (Fig. 7) is attributable to the shift in the relaxation frequency for liquid water to higher frequencies as temperature increases. At 5 °C, the relaxation frequency of liquid water is 10.7 GHz [12], and

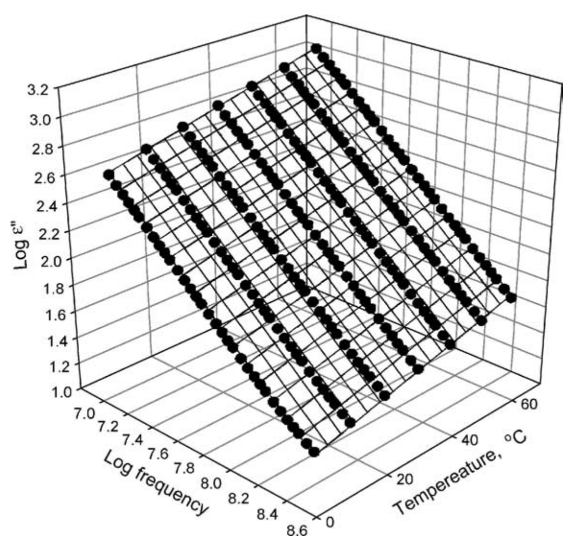

Fig. 8. Three-dimensional plot of fresh navel orange tissue loss-factor data for 10–300 MHz frequency range and 5–65 °C temperature range.

the associated dispersion begins to be evident above 1 GHz in Fig. 7 and has been noted for other fresh fruit and vegetable tissues as well [10]. The high values for the dielectric constant at low frequencies are likely attributable to the increased ionic conductivity and ionic diffusion processes contributing to the polarization at low frequencies in cellular structures [13]. There is most likely a low-frequency dispersion, possibly

Maxwell–Wagner, below the frequency range of these measurements, which also shifts to higher frequencies with temperature increase as evidenced by the data of Fig. 7. These factors, along with an ionic conductivity that increases with frequency, imply no conflict with the Kramers–Krönig relations.

5. Discussion and conclusions

A few applications have been provided in this paper that illustrate the usefulness of dielectric spectroscopy in agricultural research. Although some of the data presented were obtained tediously on many different measurement systems in order to assemble the dielectric spectroscopic information, they still serve to show the utility of such information. Later developments in instrumentation and techniques in either frequency-domain or time-domain systems make the assembly of dielectric properties information much more efficient.

As for future agricultural applications, the few examples presented here suggest others of a similar nature. Assessment of the potential for selective dielectric heating for control of insects or other organisms in agricultural products can be aided materially by the application of dielectric spectroscopy to permit an intelligent selection of frequency ranges to explore. The sensing of maturity or other quality factors in fruits and vegetables has been explored only a little. An application of interest, yet to be investigated, is the sensing or measurement of dry matter in certain products. Studies of the correlation of dielectric spectrographic information with quality factors of agricultural products may well lead to useful techniques for the rapid characterization of agricultural materials.

Dielectric spectroscopy over broad ranges of frequency may also reveal information on the binding of water in food and other agricultural materials. As more scientists and engineers develop an understanding of the potential applications for dielectric spectroscopy, further studies will be conducted, and the application of statistical techniques developed for visible and near-infrared spectroscopy may also be applied to dielectric spectroscopic data with consequent utilization of those advantages offered by radio-frequency and microwave energy for sensing and parameter measurements in agricultural products.

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